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Coronal Heating and the Magnetic Flux Content of the Network

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An appropriate title

Solar magnetic Explosions:

Flares,

Microflares

and

Solar wind

Main Points

- 1. - Flares and coronal mass ejections (or CMEs) are magnetic explosions

  - Microflares are little magnetic explosions that work the same way.

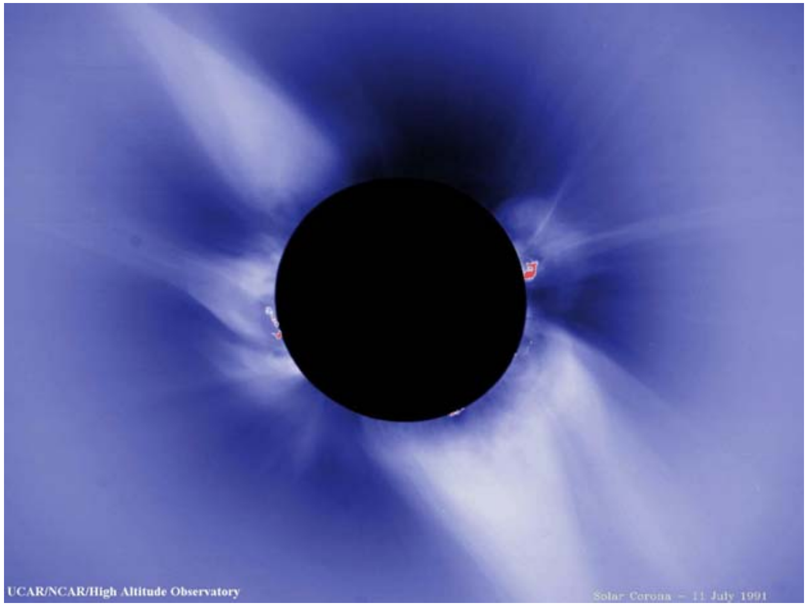
  - Microflares are plentiful enough, widespread enough, and energetic enough to heat the cornoa and drive the solar wind.
- 2. Carl Sagan's turtle joke from Cosmos; for me its magnetic explosions all way down.
- 3. If even gamma-ray bursts are made by magnetic explosions, then is it asking too much to make the Sun's corona and solar wind from magnetic explosions?
- 4. The old talk was given before we had the new observations from Yohkoh (launched in late 1991) and SOHO (launched in late 1995).
- 5. It turns out that these new observations allow me to persist in this view of coronal heating.

Outline

I. Background
- A. Corona & Solar Wind
- B. Coronal Mass Ejections & Flares
- C. Coronal Heating in Active Regions
- D. Quiet Regions

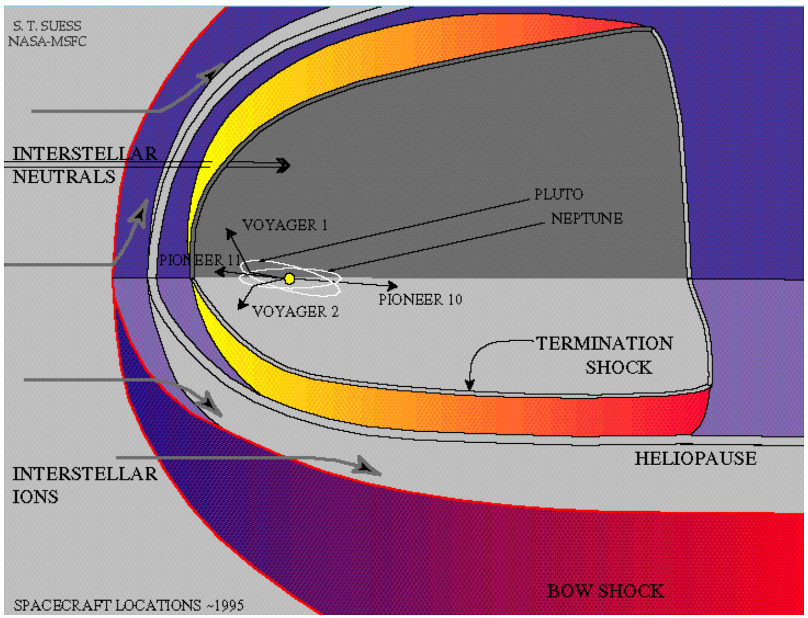
II. Coronal Heating in Quiet Regions

Eclipse corona



- - Corona seen in scattered sunlight in an eclipse.
- - Streamers are sculpted by the magnetic field as outer corona flows out to become the supersonic solar wind (solar wind speed is several hundred km/s).
- - Corona & solar wind is not a magnetic explosion per se, but a continual <u>thermal</u> explosion resulting from the corona's high temperature – a few million degrees.
- - But the heating that keeps the corona hot and flowing out – we think – comes from many little magnetic explosions in the magnetic roots of the corona down on the surface.

Heliosphere

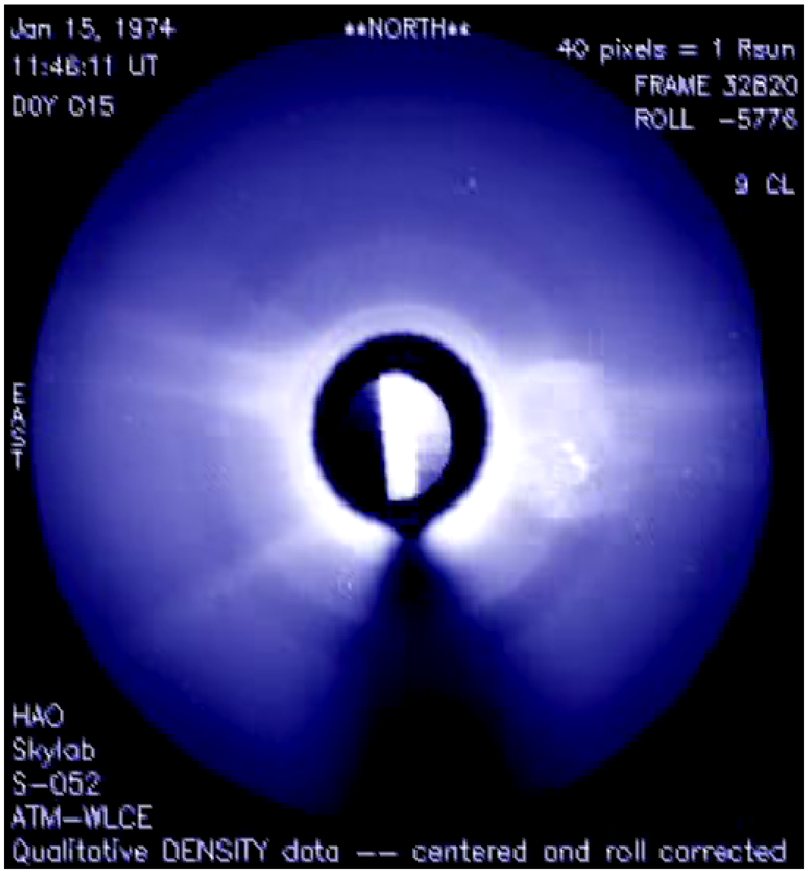


- - One of Steve Suess's pictures of the heliosphere.
- - Heliopshere is made by the solar wind in the interstellar wind, like the magnetosphere is made by Earth's magnetic field in the solar wind.
- - Because the solar wind is supersonic and is stopped by the interstellar medium, it must have a termination shock – has been expected to be at about 100 AU.
- - A Voyager probe recently crossed the termination shock at about 80 AU.
- - So coronal heating does a big job – it is the cause of the heliosphere.

Global energetics

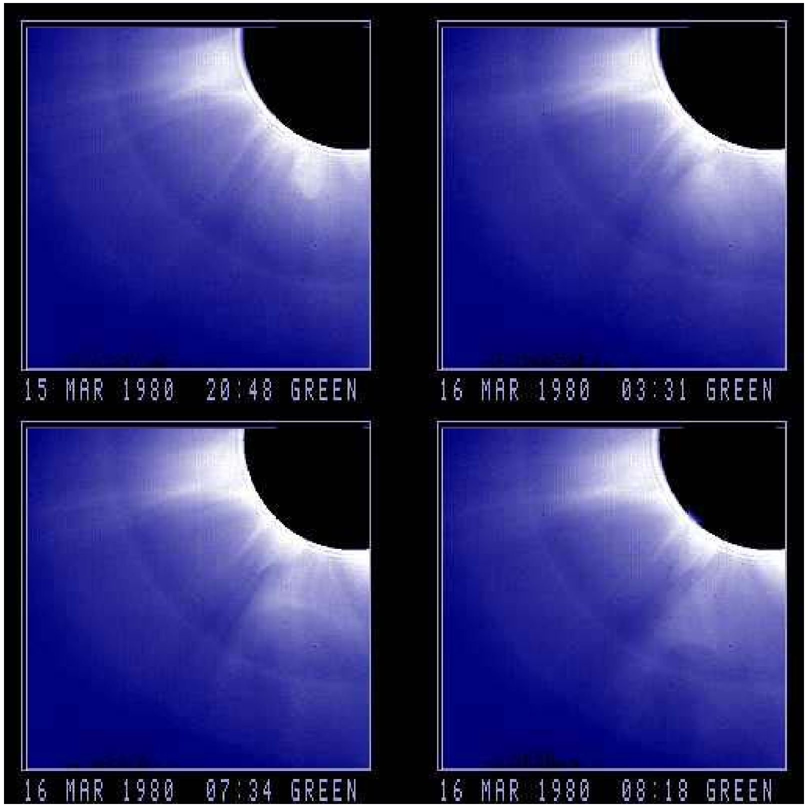
- \- Total power for corona & solar wind is 30,000 times less that the power going to sunlight.
- \- But this is still a large power requirement.
- \- Big flares don’t happen often enough to be the source – would need one about once per hour, but they happen less than once a month on average.
- \- Microflares can do it if ~ 1000 happen per second all over the Sun.
- \- From our new evidence, we think that this is the case.

Skylab CME



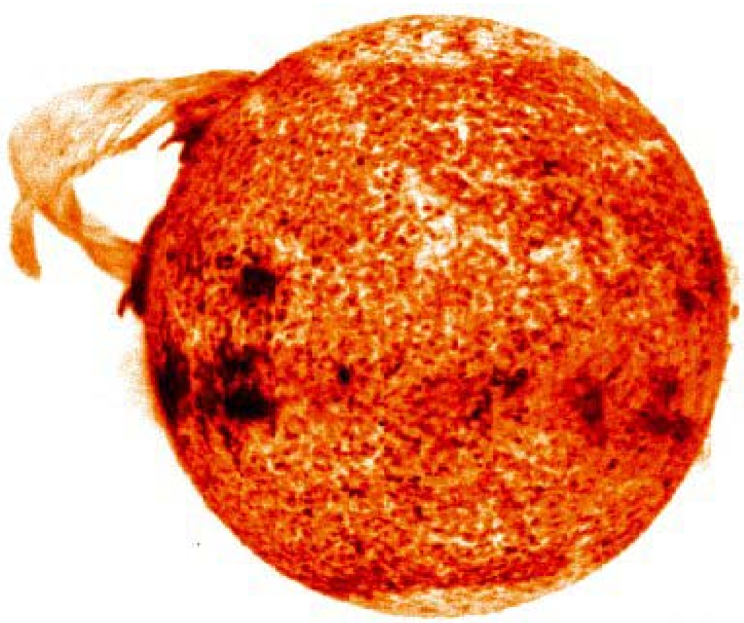
- - Famous CME image from Skylab coronagraph (30 years ago).
- - Occulting disk is twice the diameter of the Sun.
- - CME is about 4 solar radii out and already twice as big as the Sun.
- - Looks magnetic and in fact is a magnetic explosion.
- - CMEs like this are much faster than the solar wind, and so plough through it at a speed of ~ 1000 km/s.

SMM CME



- \- Famous CME image from Solar Maximum Mission, in next solar cycle after Skylab.
- \- The dense filament traces some of the exploding field in the core of the CME.

Skylab filament eruption



- \- This He II 304 image is probably the most famous image from Skylab.
- \- It shows the erupting filament in the core of a CME.
- \- Here we see only the filament, but it rides core of a CME like two I showed.
- \- The filament traces magnetic field that before exploding was low and sheared in the core of a large closed bipolar field.
- \- This one exploded from a weak-field quiet region.

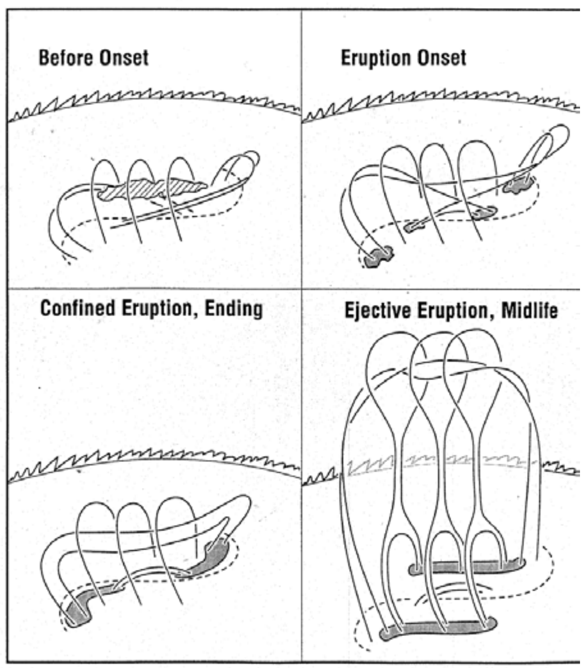
Ejective explosion from sunspot region

- - Here is a similar CME filament eruption observed in H-alpha from the ground (Big Bear).
- - But this one is from a strong-field active region with sunspots, in which the field is 10-100 times stronger that in quiet regions.
- - The biggest and fastest CMEs come from explosions of these strong fields.
- - Along with the fast CME, the explosion also makes a big flare with intense coronal heating in the active region.
- - But not all such explosions of sheared core fields make a CME. Some are confined within the closed bipole and make only a flare.

Confined explosion in sunspot region

- \- Here is a confined explosion observed in H-alpha.
- \- Before onset, the filament traces the sheared core field low along the polarity dividing line or neutral line between the opposite polarity domains of the bipolar active region.
- \- Here the filament starts to explode about like it would in CME explosion, but in this case it is stopped by the envelope of the bipole and remains confined within it.
- \- In a CME explosion the, the exploding core field blows open the bipole and goes on out through the corona, making a CME.

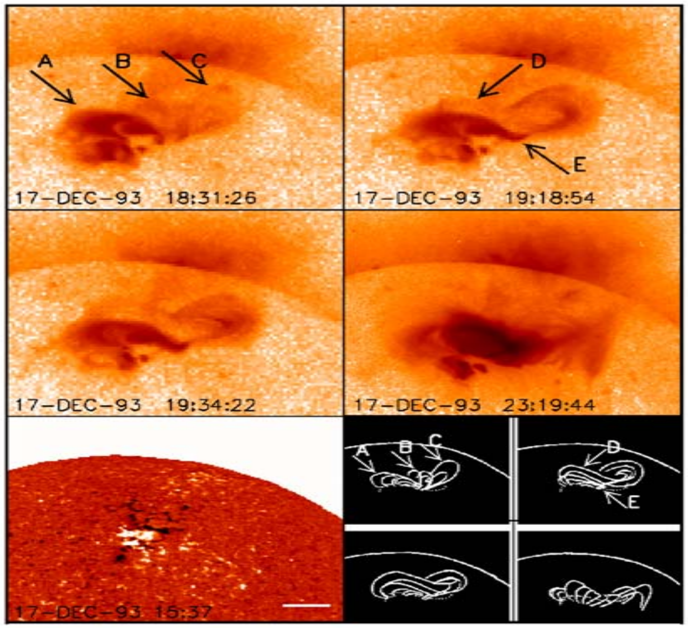
Model configuration for exploding bipolar fields



Exploding single-bipole sheared core fields.

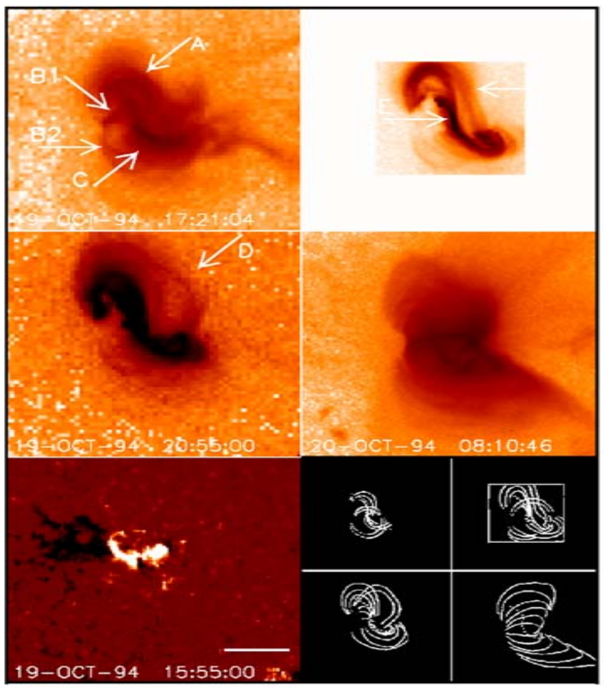
- \- Here's the magnetic set up for these explosions, either confined or ejective.
- \- Before onset: closed bipolar field with sigmoidal sheared core field partly traced by a filament.
- \- Onset: reconnection starts low in the sheared core field, releasing it to explode.
- \- Heating from the reconnection lights up the erupting sigmoid in coronal X-ray images.
- \- Confined case: the explosion is stopped before it gets very far, and the heating doesn't last nearly as long as in the ejective case.
- \- Ejective case: the core field blows open the bipole, makes a CME, and the flare heating lasts for hours as the opened field reclosed by reconnection that makes this long-lasting flare arcade seen in coronal X-ray images.

Another observed ejective explosion



- \- Bipolar active region.
- \- Sigmoidal sheared core field.
- \- Sigmoid brightens as reconnecting core field lifts off and explodes outward,
- \- Later left with long-lasting flare arcade.

Another observed ejective explosion



- \- Bipolar active region.
- \- Sigmoidal sheared core field.
- \- Sigmoid brightens as reconnecting core field lifts off and explodes outward,
- \- Later left with long-lasting flare arcade.

Example confined explosion

- Ragged bipole.
- Sheared core field before explosion.
- Explosion is a complicated reconnection and relaxation of the sheared core field within the bipole.

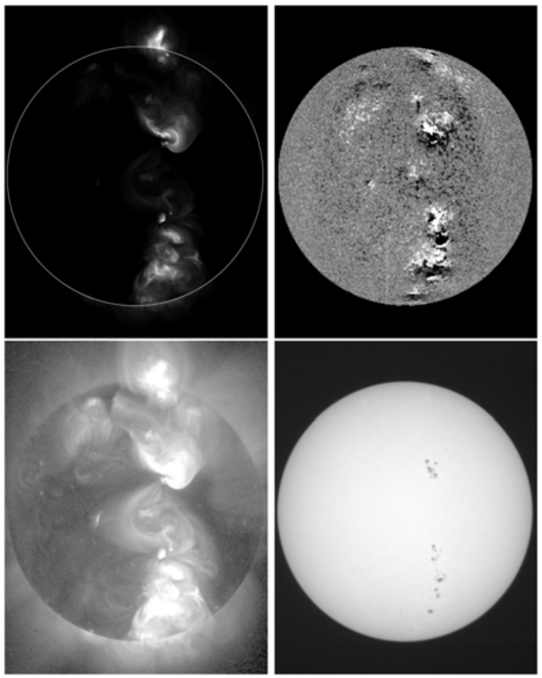
Estimation of energy released from exploding sheared core field

- \- We use this simple flux rope model for the core field to estimate the energy released in any of these explosions.
- \- For frozen-in magnetic field and isotropic expansion the magnetic energy in the flux rope decreases as 1/length scale of the flux tube as it explodes.
- \- So, as soon as the core field has expanded by more than a factor of two, it has lost most of the magnetic energy that it had at the start.

How the core-field explosion drives the flare heating

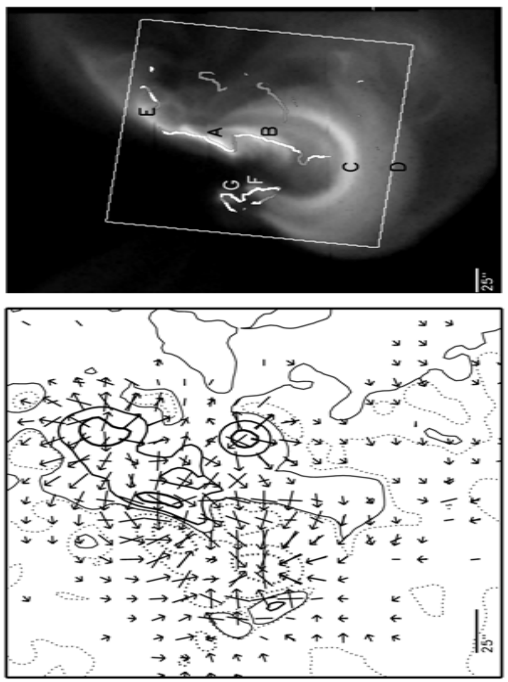
- \- The exploding core-field flux rope loses its energy by working on the surrounding field.
- \- It stretches the field around it, giving it more energy.
- \- The stretched field then reconnects, and energy originally in flux rope goes into the flare heating.

Coronal Heating in Active Regions



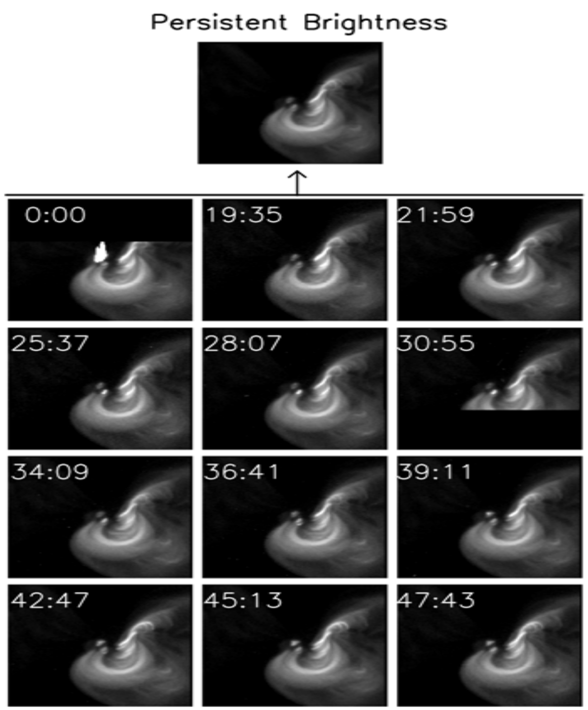
- Top left: Yohkoh X-ray corona. - Top right: Same image rescaled to show structure in brightest areas.
- - Bottom left: Yohkoh photosphere showing sunspots.
- - Bottom right: Kitt peak magnetogram.
- - Strongest coronal heating is obviously in the regions of strongest field, near sunspots.
- - In this sigmoidal active region, all of the brightest loops are rooted near polarity dividing lines – in the core of the overall bipole and at the island of included positive polarity in the negative domain.
- - We will now take a close-up look at this active region in a vector magnetogram from Mona Hagyard's observatory here at Marshall.

AR having strongest coronal heating rooted in sheared core fields



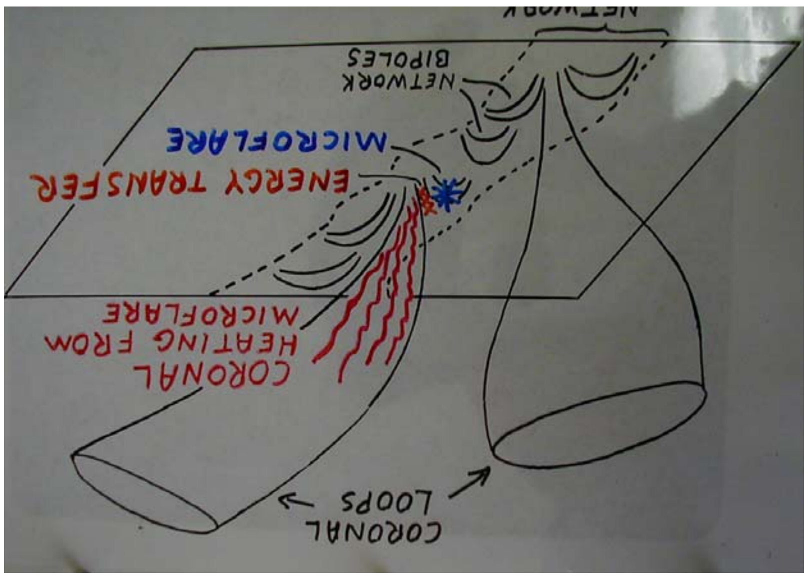
- - Left: vector magnetogram of the same active region.
- - Contours show the line-of-sight of the magnetic field in the photosphere.
- - Here's the main neutral line, and here's the island.
- - Dashes show the observed transverse field.
- - Arrows show the potential (no shear) trasverse field computed from the observed
- line-of-sight field.
- - Field is strongly sheared where the dashes are nearly perpendicular to the arrows.
- - This shows there is strong shear along the main neutral line and around the island.
- - Right: X-ray image of the active region with neutral lines from the magnetogram superposed.
- - The brightest loops, which have the strongest coronal heating, are all rooted in the sheared core fields – along the main neutral line and around the island.

Microflaring in the sheared core fields



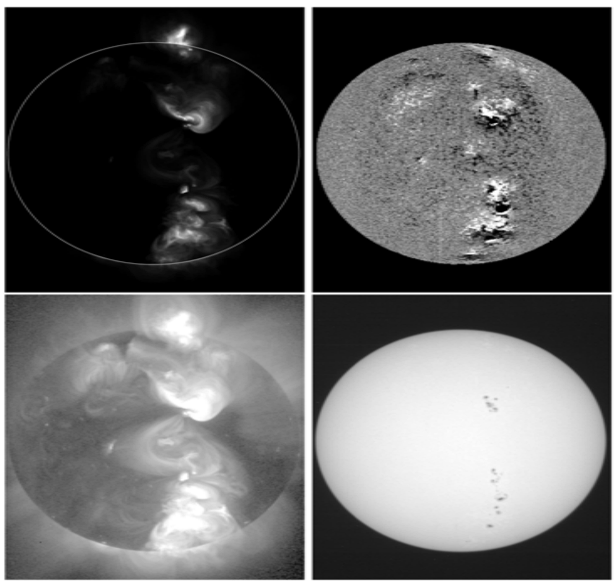
- - Series of X-ray images of the active region with a cadence of a few minurtes.
- - Shows continual microflaring in all of the sheared core fields, both along the main neutral line and around the island.
- - We think that these microflares are little confined magnetic explosion in the sheared core field, and that these explosion are the driver of the strong coronal heating in this active region.

. Picture for AR coronal heating driven by core-field microexplosions



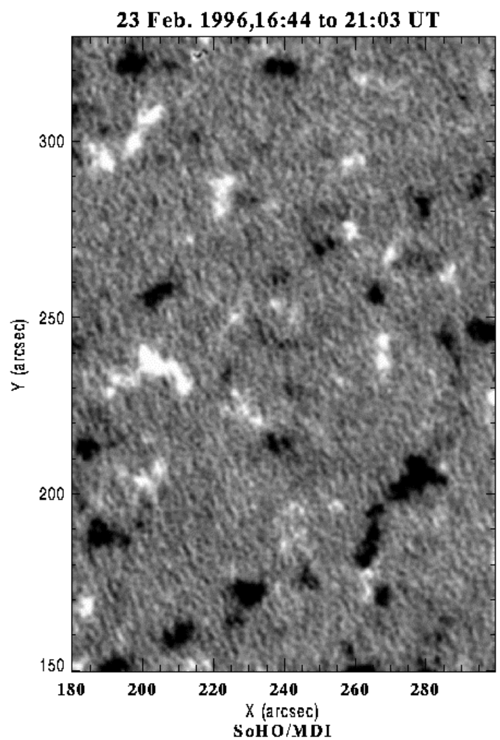
- \- Sketch of the magnetic field in our active region in a cut through the island.
- \- There are these little confined magnetic explosions on the main neutral line and at the island.
- \- Both heat themselves and send out waves to heat the rest of the active region.
- \- In addition, the explosion at the island drives reconnection at the magnetic null over the island.
- \- This results in extra heating in the extended loops involved in the reconnection.
- \- We invoke this same embedded-island magnetic set up heating the corona in quiet regions.

Quiet Regions



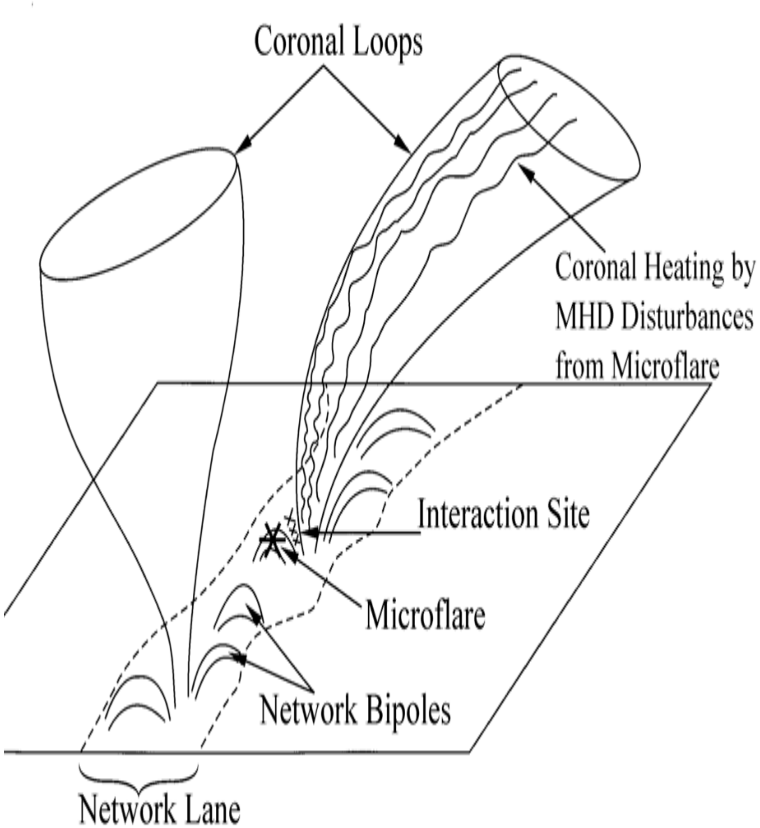
- -	Most of the corona & solar wind is rooted far from active regions, in quiet regions where:
- -	Magnetic field is much weaker than in active regions.
- Magnetic field is rooted in a network of flux clumps of

Magnetic network



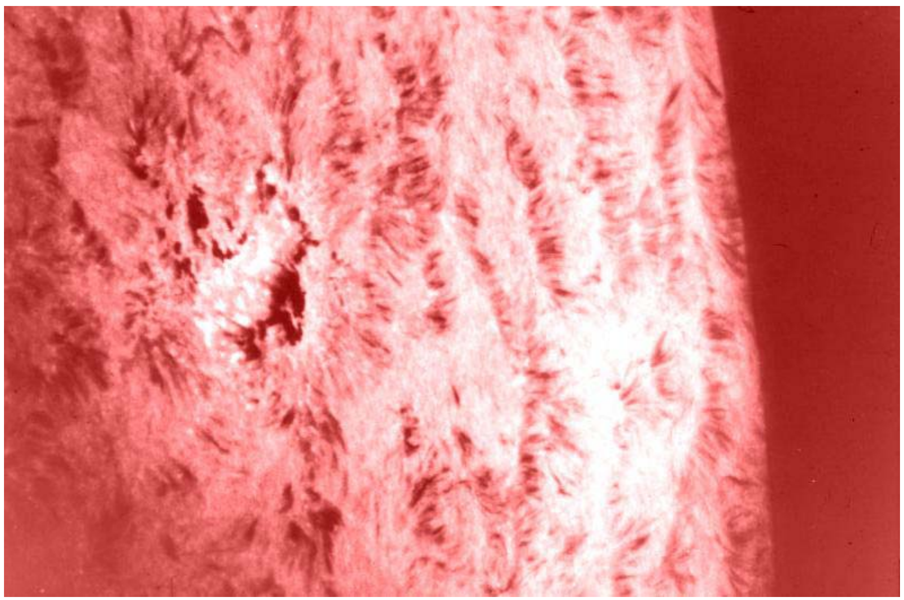
- \- Close-up magnetogram of a quiet region.
- \- Flux is in clumps in a loose network at the edges of supergranule convection cells about 30,000 km wide.
- \- Have lots of neutral lines and so lots of possible sites for microflares from little core-field explosions.

Picture for coronal heating in quiet regions



- \- Have short magnetic loops, these network bipoles, and high-reaching corona funnels rooted in a network lane at the edge of a cell.
- \- A core-field explosion in a bipole drives coronal heating via reconnection with a funnel rooted against, like in the extended loop from the island in the active region.
- \- Our new paper gives evidence that this is basically the right picture for coronal heating in quiet regions, except for the scale of the exploding bipole shown here.

Spicules rooted at cell edges

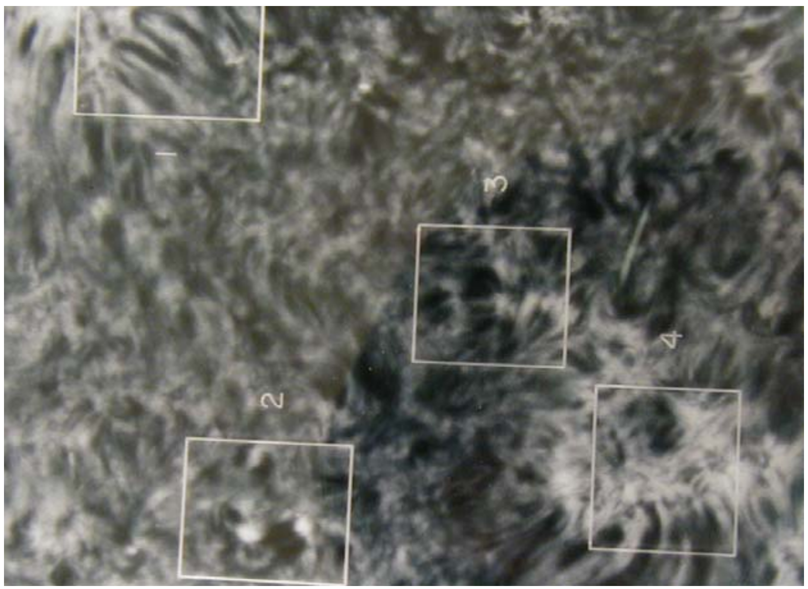


- - Famous high-resolution H-alpha image from Sac Peak.
- - Shows spicules in the magnetic network at the cell edges.
- - Each spicule is a little explosive jet-like eruption, lasting 5-10 minutes.
- - At any instant, there are roughly 30 spicules present around each cell.

Magnetogram of enhanced magnetic network

- - Here is magnetogram of network of mostly one polarity – a remnant of an old active region.
- - Note the "cell and finger" pattern.

Spicules at edges of network flux clumps



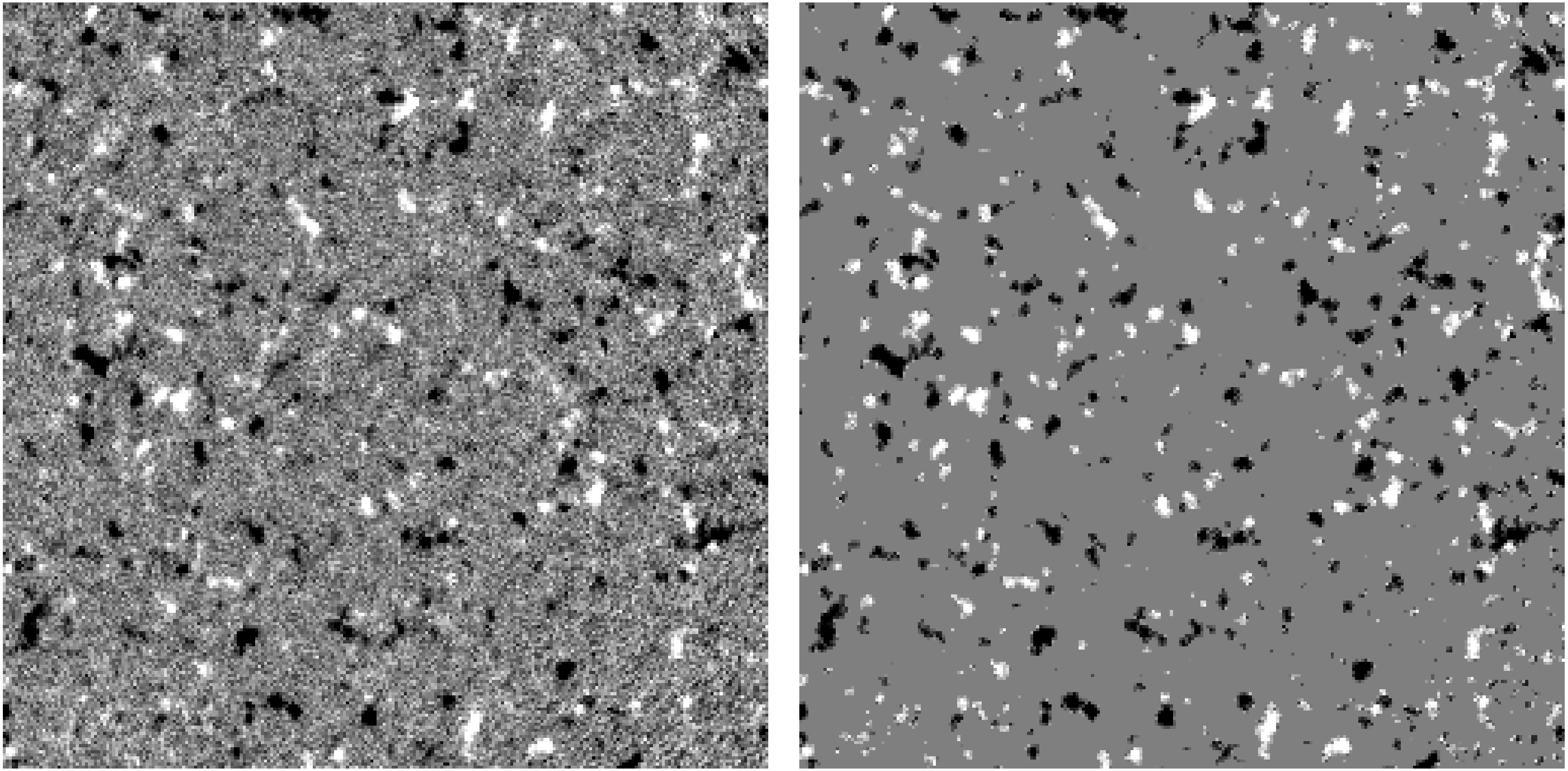
- \- Here is an H-alpha image of the same region.
- \- Here is the cell and finger.
- \- The spicules are mostly rooted at the edges of the network flux.

Coronal Heating in Quiet Regions

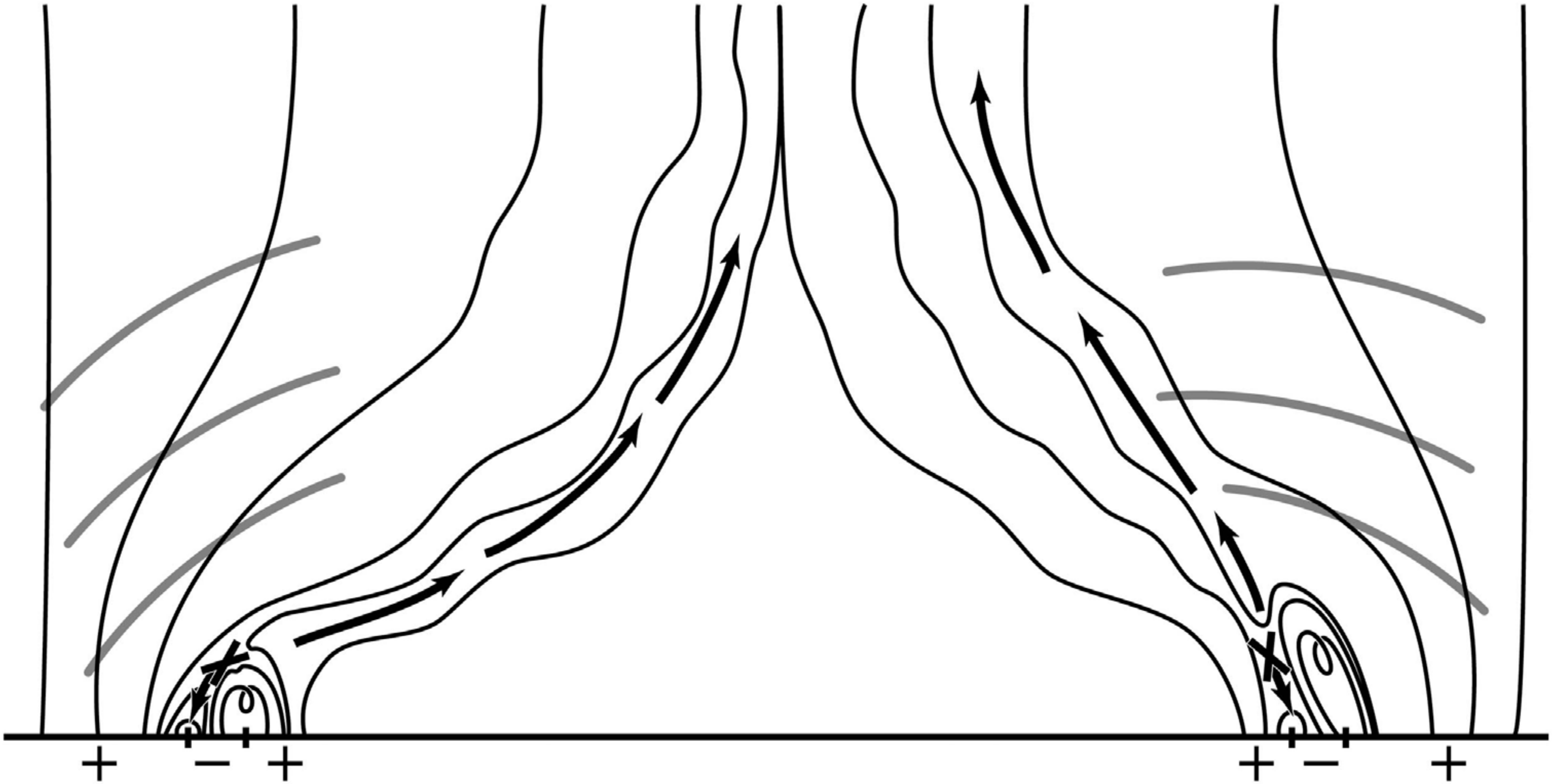
- Now ready to go into our new paper.
- Will first give the idea and picture of what we think we have found.
- Then go into the observations and how they point to this picture for coronal heating in quiet regions.

Quiet Region Magnetic Network

"Raw" **"Cleaned"**



0.5 R_{Sun} central square from MDI full-disk magnetogram
1996 Dec 28



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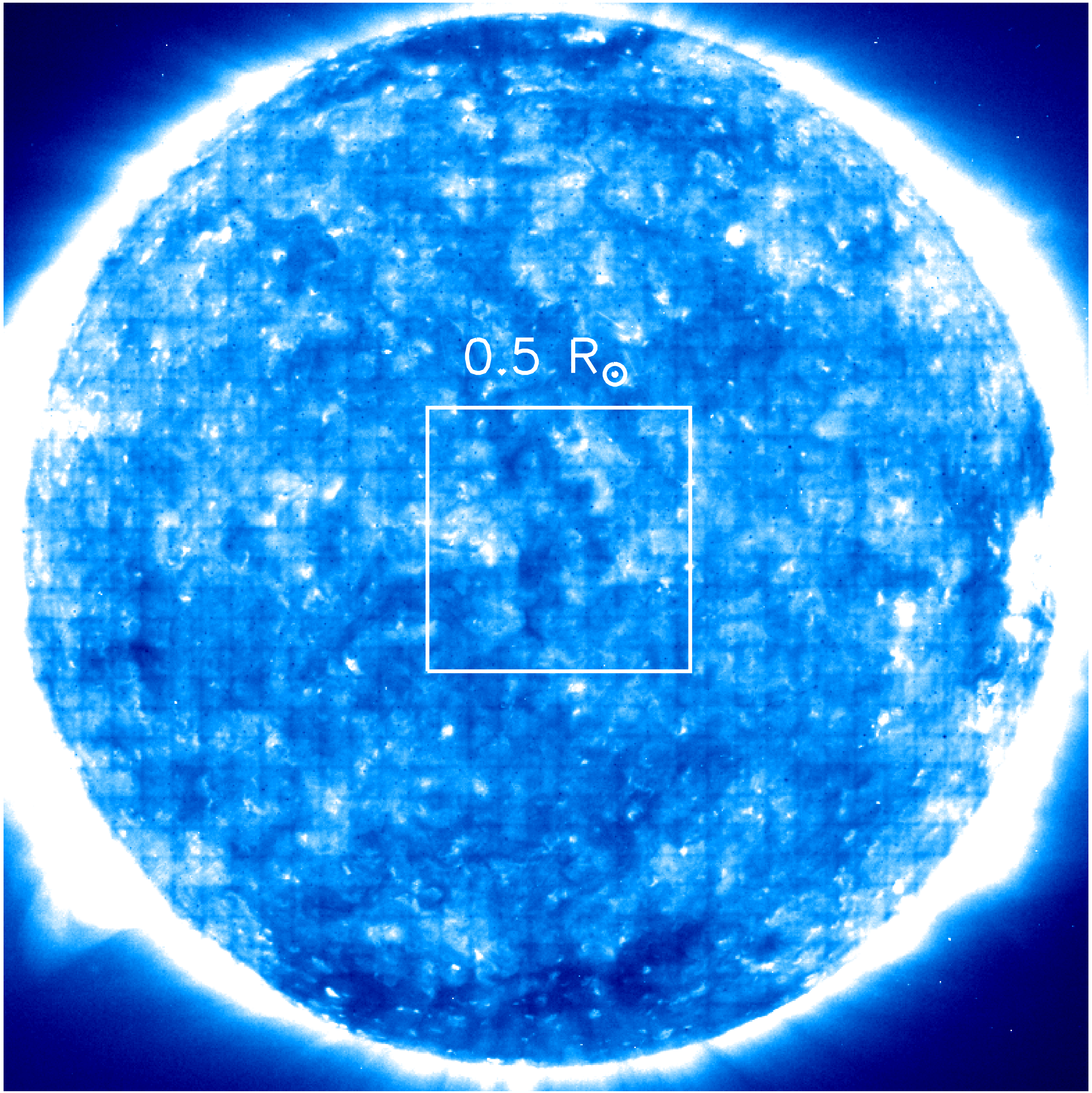
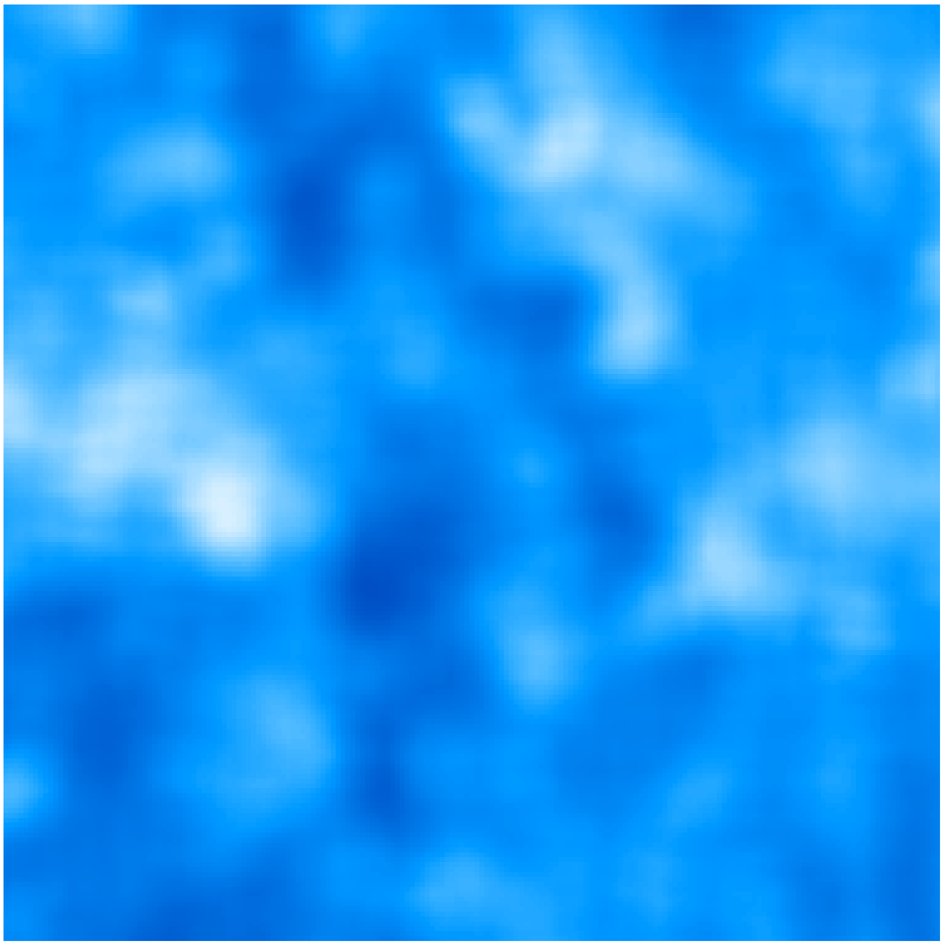
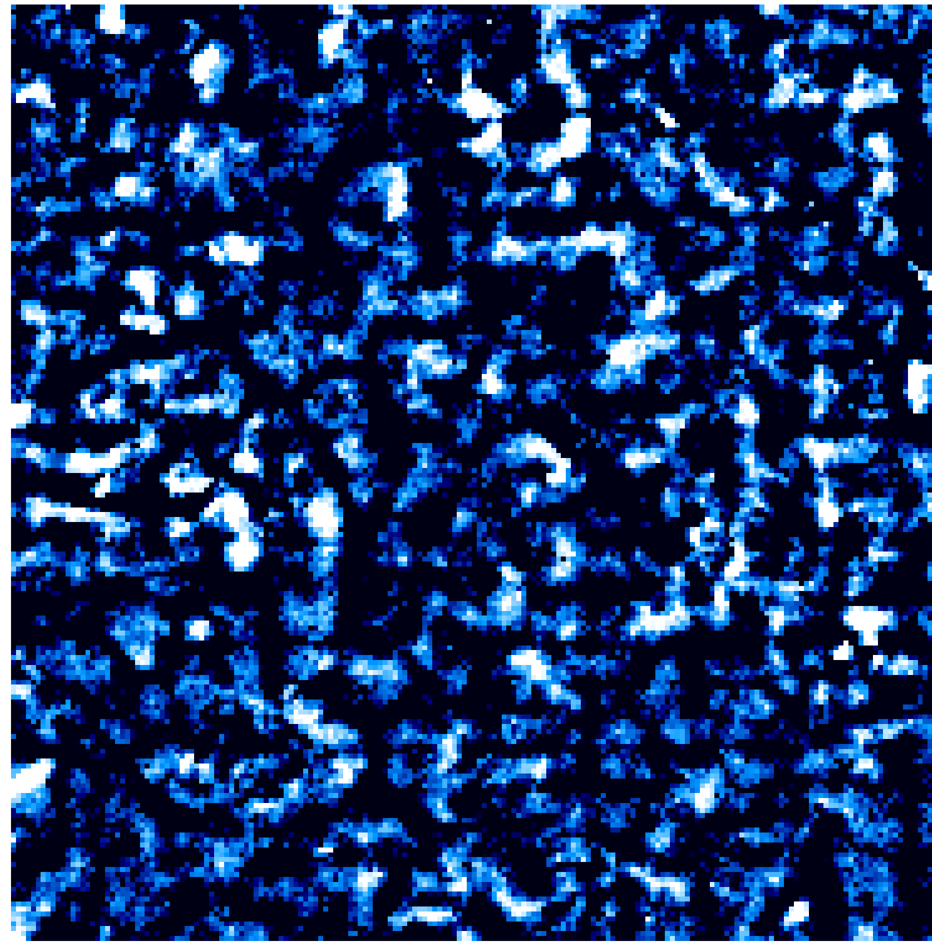
EIT Fe IX/X, 1996 Dec 28



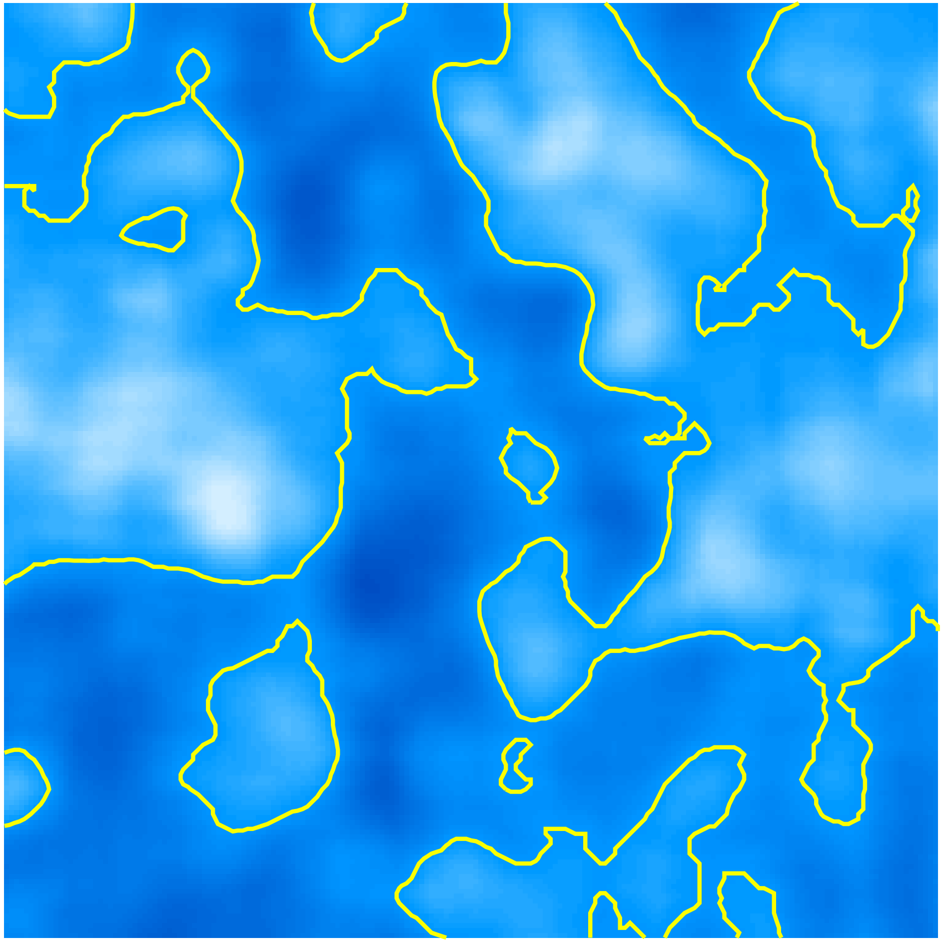
Large-Scale Corona



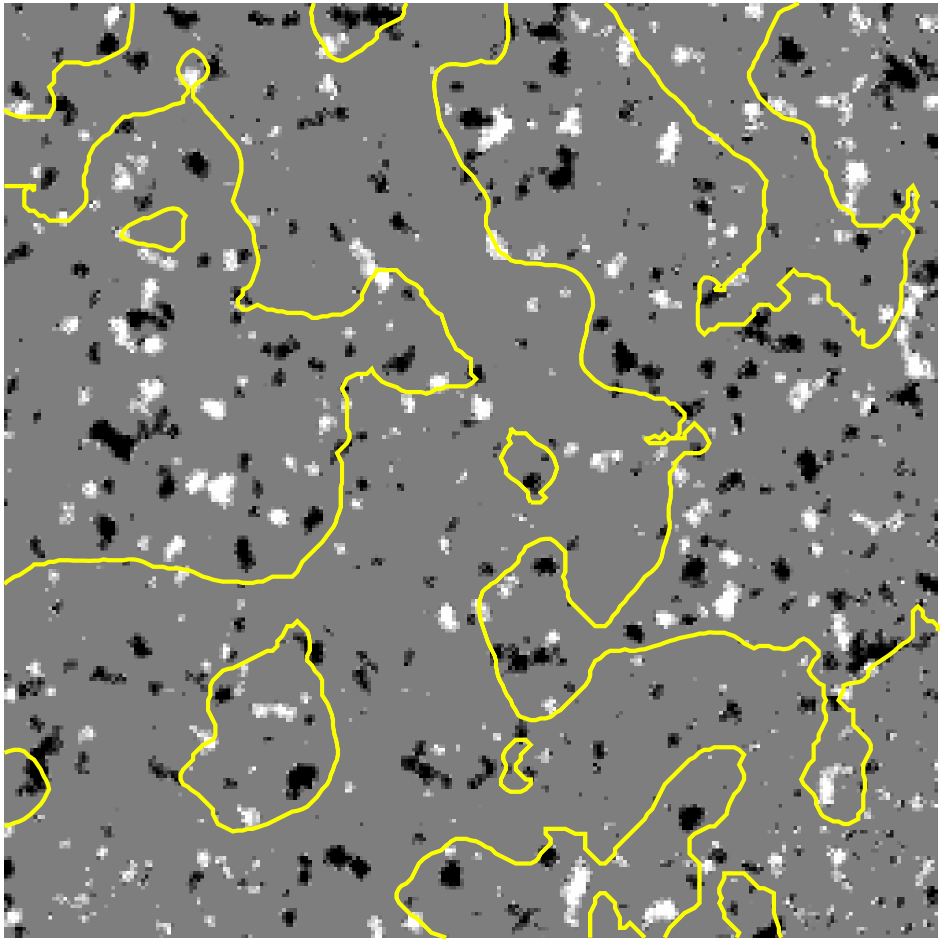
Coronal Network



Bright and Dim Halves of Large-Scale Corona



Large-Scale Corona

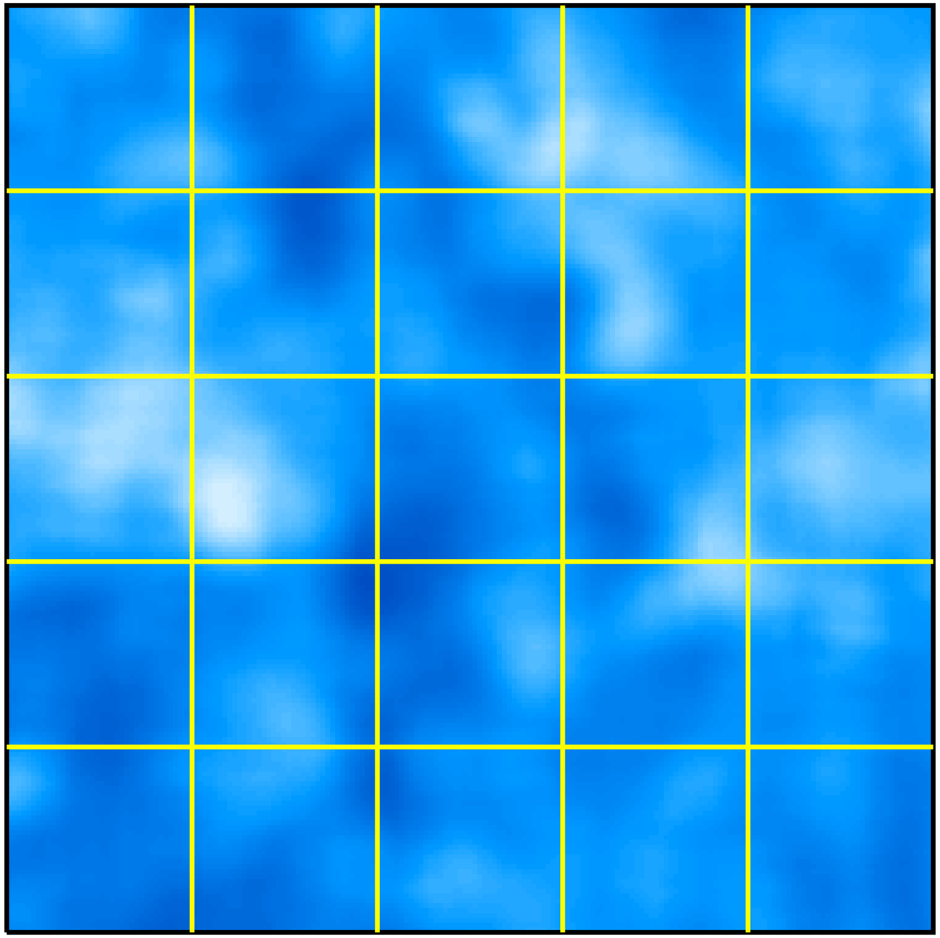


Magnetic Network

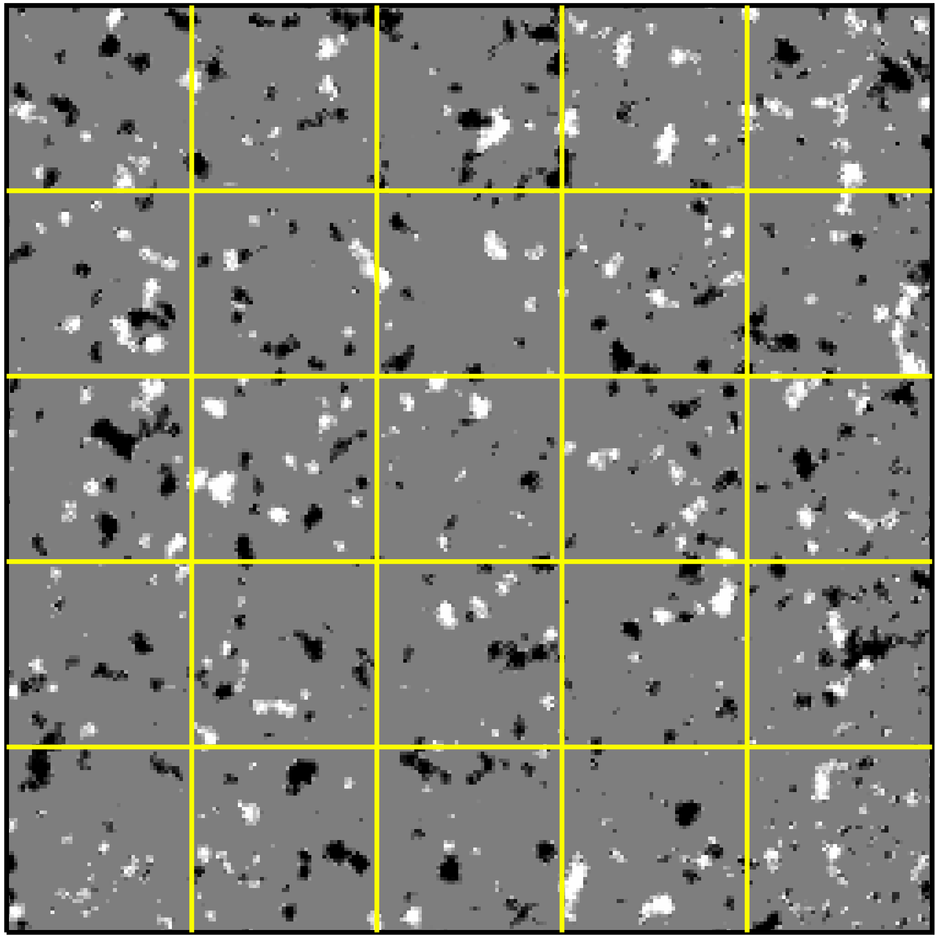
Average Fluxes of Coronal Radiation and Network Magnetic Flux in Bright and Dim Halves of Large-Scale Corona

Date (Dec 1996)	Radiation Flux (10^5 erg cm^{-2} s^{-1})		Network Magnetic Flux (Gauss)	
	Dim Half	Bright Half	Dim Half	Bright Half
27	0.93	1.2	1.3	2.7
28	0.97	1.3	1.2	3.3
29	0.96	1.3	1.5	2.9
30	0.95	1.3	1.6	3.1
Average:	**0.95**	**1.3**	**1.4**	**3.0**
Bright/Dim Ratio:	**1.4**		**2.1**	

5x5 Grid of Constant-Area Samples

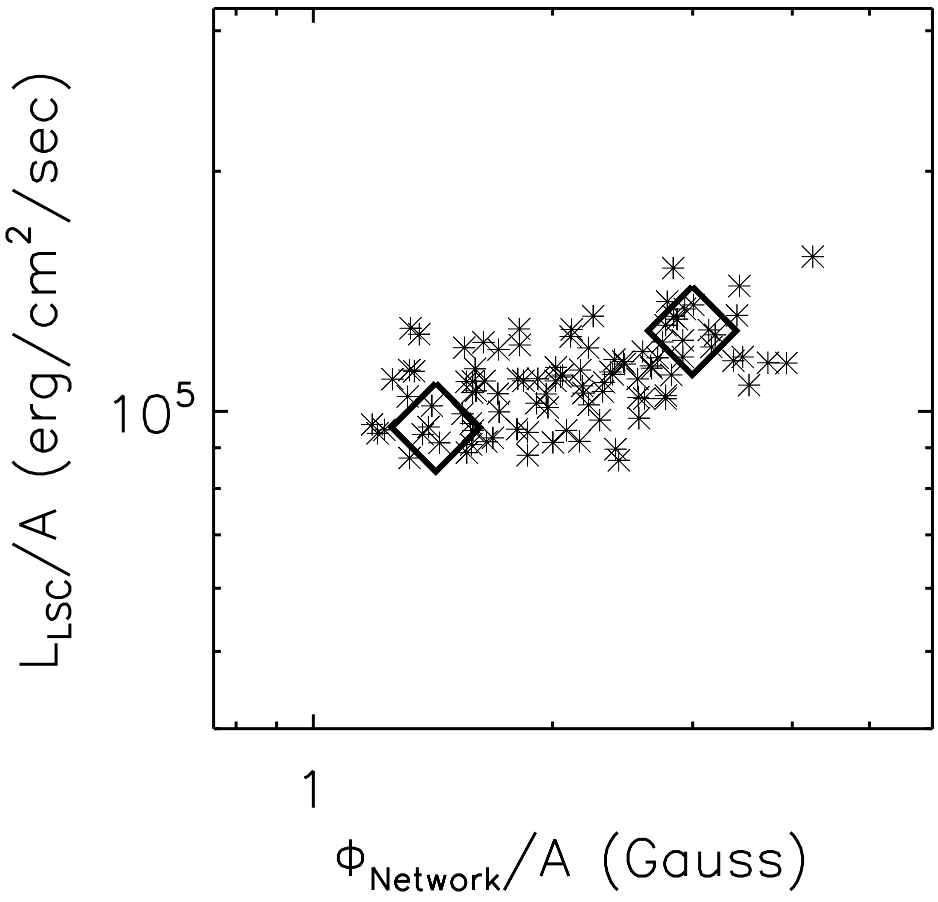


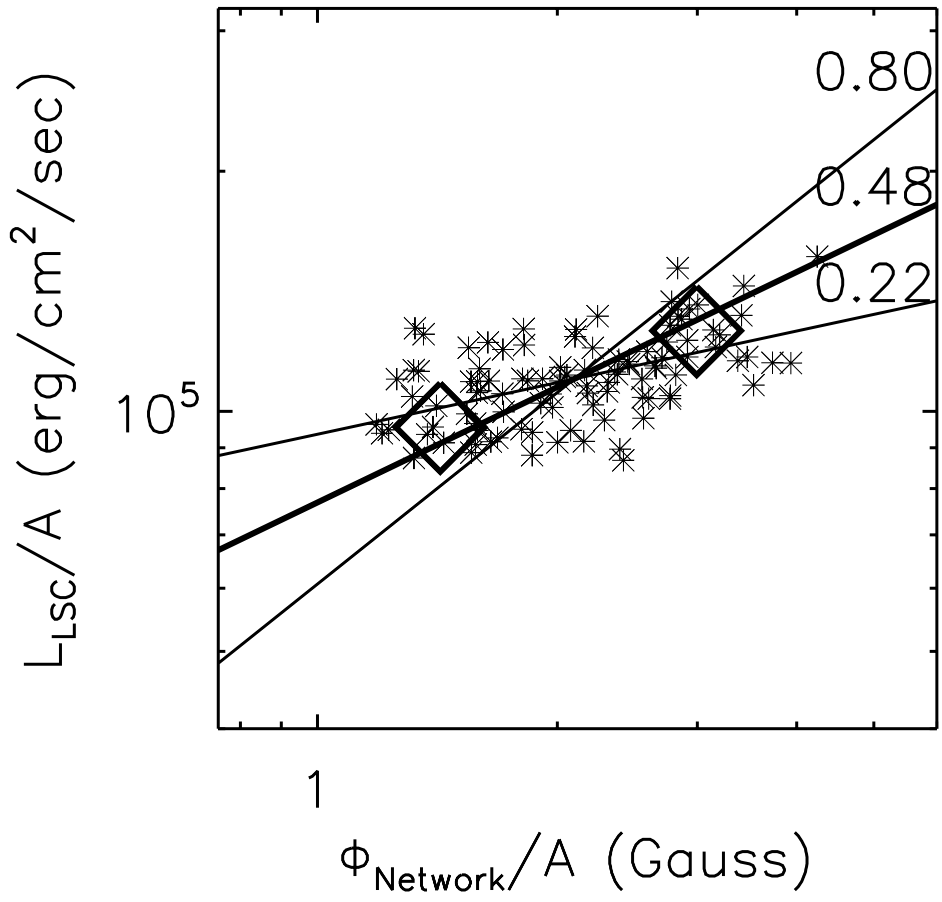
Large-Scale Corona



Magnetic Network

Increase of LSC Luminosity with Network Magnetic Flux





Magnetic network in bright & dim halves

- \-   The magnetic network in the bright half looks like the network in the dim half except that it covers more are in the bright half.
- \-   This suggests that the luminosity scales as the square-root of the area of the network flux, and this in turn suggests that the luminosity increases in direct proportion to the total perimeter length or coast length of the network flux.
- \-   To test this idea, we measured the total network coast length in the bright and dim halves on each of the four days, to see what factor of increase that has.

Average Fluxes of Coronal Radiation and Network Magnetic Flux and Length of Network Flux Coastline in Bright and Dim Halves of Large-Scale Corona

Date (Dec 1996)	Radiation Flux (10^5 erg cm^{-2} s^{-1})		Network Mag. Flux (Gauss)		Ntwk. Flux Coast Length (10^6 km)	
	Dim Half	Bright Half	Dim Half	Bright Half	Dim Half	Bright Half
27	0.93	1.2	1.3	2.7	5.2	6.8
28	0.97	1.3	1.2	3.3	5.2	8.0
29	0.96	1.3	1.5	2.9	5.9	6.9
30	0.95	1.3	1.6	3.1	5.8	7.0
Average:	**0.95**	**1.3**	**1.4**	**3.0**	**5.5**	**7.2**
Bright/Dim Ratio:	**1.4**		**2.1**		**1.3**	

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